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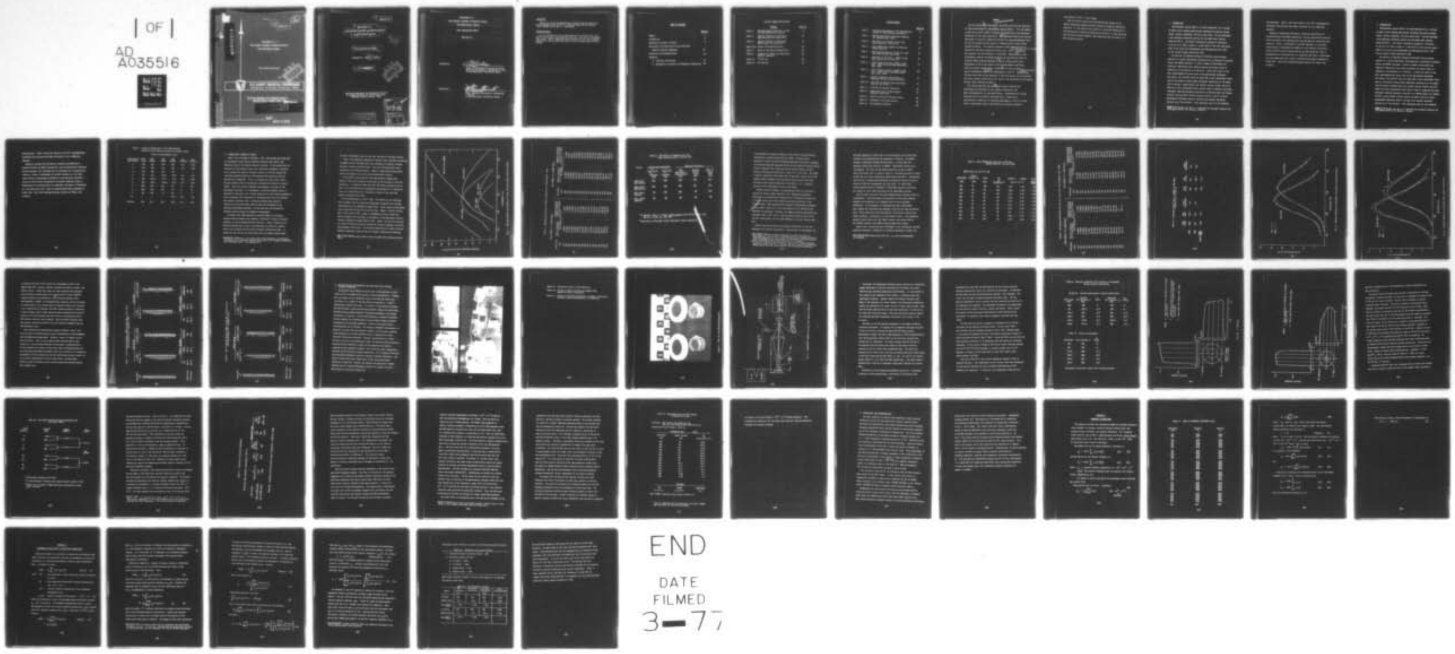

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DEVELOPMENT OF A

HIGH ACCURACY LUMINANCE CALIBRATION SERVICE

FOR RADIOLUMINOUS SOURCES

Final Engineering Report

U.S. ARMY MISSILE COMMAND

Redstone Arsenal, Alabama 35809

Metrology Development and Engineering Division
U. S. Army Metrology and Calibration Center
Redstone Arsenal, Alabama 35809

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Prepared by: Major L. Fecteau

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FINAL ENGINEERING REPORT

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DISCLAIMER

Mention or use of any manufacturer's product does not constitute an endorsement either by the U. S. Army Metrology and Calibration Center (USAMCC) or by the U. S. Government.

ACKNOWLEDGEMENTS

It is a pleasure for me to acknowledge the assistance of Ms. Mary Mancil in data taking and reduction and of Mr. Larry Sills in preparing this report. Messrs. Woodliffe, Webb and Harder of the Army Standards Laboratories also assisted from time to time in system setup and data-taking.

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SUMMARY

HAS BEEN DEVELOPED

We have developed a technique for accurately measuring the luminance of (quasi-monochromatic) radioluminous sources (RLS's). This development is part of an overall effort to improve the specification and subsequent procurement of low light level RLS's. ~~Our~~ THIS technique involves the accurate measurement of spectral radiance of the RLS via a spectroradiometer which has been calibrated directly against a freezing point of gold primary standard blackbody. The spectral radiance is then combined with the appropriate luminosity weighting function (e.g., the C.I.E. (CHROMATICITY DIAGRAM) photopic eye response), and the luminance is calculated. Measurements on four radioluminous sources calibrated previously by the National Bureau of Standards (NBS) produced agreement to +or− ±1% for three sources; and a disagreement of 3% on one source at the 50 microlambert ~~(μl)~~ level. Since our process repeatability is about +or− ±2%, we have assigned an overall uncertainty of + or minus ±3.6% for measurements in the 25 - 1500 MICROLAMBERT ~~(μl)~~ range. The main restriction in our technique is that the sources to be calibrated must have a planar surface area of at least 21 and preferably 25 millimeters diameter which radiates uniformly.

This report describes ~~our~~ measurement system including the development and refinement of the system's calibration, and makes recommendations for continued efforts. Recommendations include: Disseminating the accurately calibrated RLS's, conducting an interlaboratory comparison of luminance measurements of RLS's (a round robin or measurement audit), and extension of accurate luminance

measurements to the 1 - 10 μl range.

This calibration service will be offered upon receipt of our Nuclear Regulatory Commission (NRC) License for handling radioactive materials. In the interim, this service is available immediately if the radioluminous sources are hand-carried to the U. S. Army Metrology and Calibration Center (USAMCC), thus remaining under the control of NRC licensed personnel.

1. INTRODUCTION.

Radioluminous sources (RLS's) are used extensively for a variety of night vision lighting applications including fire-control aiming stakes, lensatic compasses, and wrist watch dials. We have developed a new luminance calibration service for low-light-level sources, especially RLS's. The overall uncertainty assigned to luminances in the 25 μl to 1500 μl range is ±3.6%, which is the root sum square (RSS) of our worst-case disagreement with NBS-measured RLS's (3%) and our system 2-sigma imprecision (±2%).

The need for an improved luminance calibration service became apparent in a recent measurement intercomparison, conducted by Frankford Arsenal and MERDC* personnel, in which a number of Government and industrial laboratories were asked to measure and assign values of luminance in microlamberts to a few RLS's. Colors and levels of the RLS's approximated the levels used in the applications mentioned: one "green," one "yellow" source of about 300 μl each represented levels used in fire-control aiming stakes (hereafter referred to as "Hi Green" and "Hi Yellow," respectively); one "yellow" and one "green" source of about 60 μl each represented levels usually found in compasses and other instrument lighting (hereafter referred to as "Medium Green" and "Medium Yellow"); and two other "yellow" sources of about 5 and 12 μl which approximated luminances found in various wrist watches (hereafter referred to as "Low Yellow"). Each laboratory used its own standards

*MERDC is an acronym for the U. S. Army Mobility Equipment Research and Development Center, Fort Belvoir, Virginia.

and techniques. Table 1 gives the results of the 1971 intercomparison: variations from the mean were ±50%; variations of up to 300% were reported.

Working in conjunction with Messrs. Gonsherry and McMillan of Frankford Arsenal and MERDC respectively, and also NBS Optical Radiation Section personnel, the following plan was developed for correcting this situation: Phase 1, Development of new NBS standards for low-light-levels; Phase 2, Development by USAMCC of a new luminance calibration service for RLS's which incorporated the new NBS standards; Phase 3, Dissemination of calibrated RLS's as standards; and Phase 4, Performance of a new round-robin with a goal of producing measurement agreement to within ±15%. This Final Engineering Report details our Phase 1 and 2 efforts.

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Table 1. Luminance Measurements of Six Radioluminous Sources at Participating Laboratories (Summer, 1971)

Values in Microlamberts (μL)

Participating Laboratories	High Green	High Yellow	Med. Green	Med. Yellow	Low Yellow 1	Low Yellow 2
1	450	350	150	105	5.5	15.0
2	455	380	145	108	5.5	16.0
3	450	360	149	114	-	-
4	317	313	103.5	93.8	4.0	11.7
5	358	240.3	117.5	73.3	6.3	10.0
6	302	209.1	95.39	81.6	3.6	10.4
7	356	289	119	91	5	16
8	298	238	153	83	2	11
9	152	230	47	58	2	7
10	-	-	-	32.5	2.8	5.4
Averages	350	315	120	89.7	4.2	12.1

2. CHRONOLOGICAL SUMMARY OF EVENTS.

Phase 1 was initiated in September, 1973. Discussions were held with Dr. Kostkowski, Chief, Optical Radiation Section, NBS, and Mr. Don McSparron, also of the Optical Radiation Section. It was agreed that the only way to significantly improve low-light-level photometric standards was to measure the spectral radiance, combine it with the appropriate luminosity weighting function, and calculate the resulting luminance by numerical integration. This is so because, at these light levels, the eye response shifts from photopic to mesopic and finally to scoptic vision. Thus, the correct luminance value becomes a function of the measurement technique: If a photometer is used the probable result is photometric luminance*; but if human observers are used (visual photometry) their assignments will definitely be affected by the level of luminance. We reasoned, therefore, that a luminance standard whose spectral radiance was accurately known could be made less dependent on the luminance measurement technique. At the same time, the photometric standards would be based on radiometric measurements.

In October 1973, NBS undertook to provide USAMCC two evacuated, tungsten ribbon-filament lamp standards, calibrated in terms of spectral radiance, at levels appropriate with the RLS's. Messrs. Gonsherry and McMillan provided the six RLS's described above to assist in setting levels, and to obtain the first RLS's directly calibrated by NBS. It turned out that the two Low Yellow RLS's did not produce enough signal

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*Photometric luminance is the result only if the photometer is accurately calibrated and its spectral response matches the C.I.E. photopic luminosity curve reasonably well. (See Appendix B.)

for NBS's measurement setup so they were returned to Frankford Arsenal.

Phase 1 was nominally completed in February 1974, when NBS transferred to USAMCC the two low-light-level lamp standards of spectral radiance and their related calibration data. The four calibrated RLS's were transferred to Frankford Arsenal*. Figure 1 shows qualitatively NBS's results and Tables 2 and 3 give their quantitative results.

Uncertainties associated with the lamp spectral radiance were placed at ±3%, with an overall uncertainty of ±5% assigned to the RLS's luminances. It should be noted that this NBS effort represents one of their first disseminations of photometric measurements on a radiometric base, yet uncertainties were comparable to those of the usual NBS Standard Luminance Test Plate.

We initiated Phase 2 in April 1974. This phase was not completed until December 1975 but reasonable measurement agreement with the NBS-calibrated RLS's was achieved in August 1975. Three stages of development can be identified during this period of time: Stage 1, Initial Efforts, April 1974 to April 1975; Stage 2, Development of Basic Capability, April to August 1975; and Stage 3, Refinement of the Measurement System's Accuracy, September through December 1975. Stage 1 can best be described as a time of failure and also of inactivity (owing to manpower priorities and equipment limitations). We initially hoped that our regular spectral radiance comparator, which we use for transfer calibration of NBS-type

*We, as yet, did not have an NRC license to handle the tritium-activated RLS's.

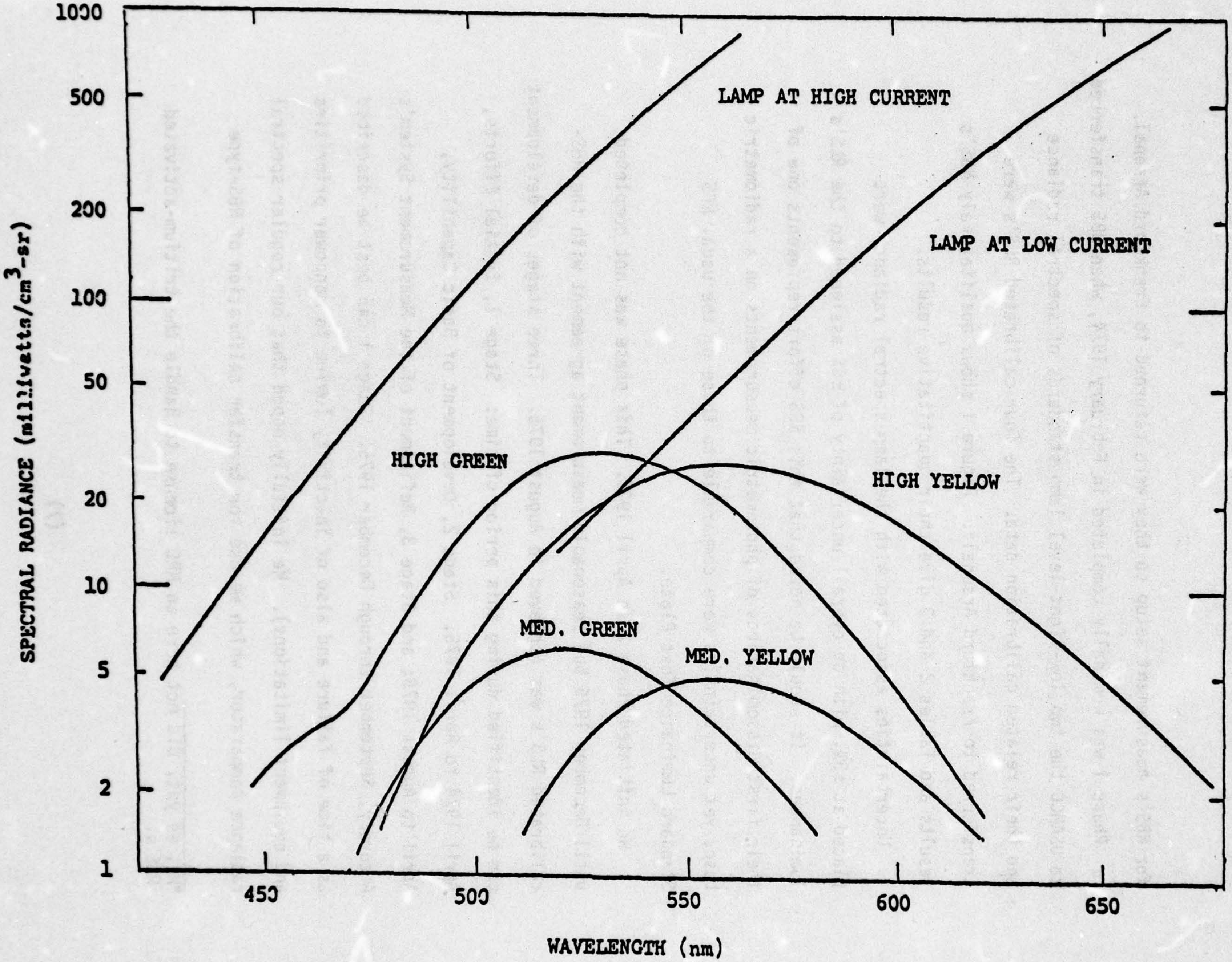


Fig. 1. NBS Approximate Calibration of Lamp and Four Radioliminous Sources

Table 2. NBS Measured Values of Spectral Radiance for Lamp Q33 (Feb. 1974)

HIGH CURRENT (I= 4.0844 Amps)

Wavelength (nm)	Spectral Radiance .6 X .8 mm Target ($\text{milliwatts}\cdot\text{cm}^{-3}\cdot\text{sr}^{-1}$)	Gradient-corrected Spectral Radiance .6 X 5.6 mm Target ($\text{milliwatts}\cdot\text{cm}^{-3}\cdot\text{sr}^{-1}$)
410	1.99387	1.9623
420	3.43876	3.38404
430	5.77107	5.67875
440	9.44159	9.29022
450	15.0877	14.844
460	23.5837	23.2011
470	36.1128	35.5245
480	54.2461	53.3587
490	80.0294	78.7151
500	116.09	114.175
510	165.756	163.014
520	233.171	229.302
530	323.454	318.07
540	442.797	435.405
550	598.677	588.655
560	799.994	786.568
570	1057.23	1039.45

LOW CURRENT (I= 3.4824 Amps)

Wavelength (nm)	Spectral Radiance .6 X .8 mm Target ($\text{milliwatts}\cdot\text{cm}^{-3}\cdot\text{sr}^{-1}$)	Gradient-corrected Spectral Radiance .6 X 5.6 mm Target ($\text{milliwatts}\cdot\text{cm}^{-3}\cdot\text{sr}^{-1}$)
520	13.5882	13.3109
530	19.8813	19.468
540	28.6257	28.02
550	40.5972	39.7237
560	56.7574	55.5164
570	78.2874	76.5494
580	106.61	104.209
590	143.432	140.157
600	190.722	186.359
610	250.972	245.095
620	326.784	319.042
630	421.323	411.232
640	538.159	525.134
650	681.302	664.652
660	855.235	834.14
670	1064.9	1038.41
680	1315.83	1282.83
690	1613.93	1573.15

Table 3. NBS Values of Luminance for the Four Calibrated RLS's (10 Oct 73)

Source	Calculated Luminance[a]		Measured Luminance		
	$K_m\int_\lambda L_\lambda V_\lambda \, d\lambda$ Photopic (μL)	$K'_m\int_\lambda L_\lambda V'_\lambda \, d\lambda$ Scotopic (μL)	NBS Photometer Measurement[b] (μL)	Nominal Stated Value (μL)	Mean of Other Labs (μL)
High Green (#4 E7263-5)	369	846	463	300	350
High Yellow (#3 E7263-4)	443	572	643	410	315
Med. Green (#50707)	68	187	109	48	120
Med. Yellow (#50706)	72	89	85	56	84

[a] G. Wyszecki and W. S. Stiles, Color Science (John Wiley & Sons, Inc., New York, 1967), pp. 378, 384.

[b] Made using a wide-angle visual photometer (three observers)

lamp standards of spectral radiance, would suffice; and positioning equipment was ordered to hold the new lamps*. An alternative approach of using a portable telespectroradiometer was held in abeyance. The standard comparator approach failed and was abandoned because typical signals produced by the lamps were barely usable, whereas the RLS spectral radiances were typically a factor to 5 to 15 lower. We needed a spectral comparator which could look at the small target area of the standard lamps (filament width was about 2 mm) but could also take advantage of the large uniform area of the RLS's, i.e., a spectral comparator with a selectable field of view (FOV).

Towards the end of Stage 1, we demonstrated that our alternative approach of using a Gamma Scientific, Inc. Telespectroradiometer, operated at its minimum focal distance and 6' FOV could be focused to a circular target area whose diameter was about two-thirds of the filament width. When operated with a Brower 131 Synchronous Voltmeter System, signal levels were a very satisfactory 10 to 100 millivolts, depending on wavelength. Moreover, the Gamma Telespectroradiometer had selectable FOV's of 20' and 1°, offering nominal optical gains of 10 and 100, respectively, for the lower radiance, but larger target area, RLS's.

Stage 2 began with setup and wavelength calibration of this new comparator in a new RLS laboratory**. We were able to intercompare the

*Our regular spectral radiance comparator consists of a Cary 14 Monochromator, transfer optics, appropriate sensor (photomultiplier or lead sulfide detector); and a Brower 131 Synchronous Voltmeter System, whose components are described elsewhere in this report.

**It was also determined during Stage 1, that an NRC license would be required to handle the RLS's; and that the RLS's posed an unacceptable safety hazard to normal Army Standards Lab calibration operations.

two lamp standards to within ±2% at all wavelengths; and at both lamp currents, thus demonstrating the comparator's linearity. We looked forward to measuring the NBS-calibrated RLS's. In May 1975, Mr. Gonsherry handcarried the RLS's to USAMCC. Measurement results were unacceptable. Our data for the Medium Green RLS, as well as NBS's data from October 1973, is given in Table 4: Discrepancies were in excess of 20% with our values consistently being higher than NBS's. Considering that the RLS's luminance had decreased by radioactive decay at least an additional 15%, the disagreement was very large. At least these results demonstrated our foresight in having NBS accurately calibrate RLS samples to cross-check and prove out our measurement process.

The four RLS's and one of the lamp standards were returned to NBS for recalibration. They discovered a 4% systematic in the lamp standard; meanwhile we discovered a six nanometer error in our wavelength calibration. In late August, we remeasured the four recalibrated RLS's against the remaining lamp standard, using the new lamp calibration data*. While there were some discrepancies, satisfactory results were finally achieved - see Tables 5, 6, and Figures 2 and 3. The luminances agreed to better than 5% on the "High" sources, and to about 12% on the "Medium" sources, with USAMCC being systematically higher.

Stage 3 was a 4-month period of refinement in our calibration and data reduction procedures, culminating in luminance agreement to within ±1%

*Our previous data demonstrated that the lamps were interchangeable as standards.

Table 4. Early USAMCC Data Compared to NBS Data, Medium Green RLS (19 June 1975)

Optical Gain, G_o (6'/1°) = 105

Wavelength (nm)	Brower Voltage, V_b (mv)	V_b/G_o (mv)	R_{L_λ} $\left(\frac{mv}{w \cdot cm^{-3} \cdot sr^{-1}}\right)$	L_λ(AMCC) $(mw \cdot cm^{-3} \cdot sr^{-1})$	L_λ(NBS) $(mw \cdot cm^{-3} \cdot sr^{-1})$	Ratio $\left(\frac{AMCC}{NBS}\right)$
490	52	.495	147	3.37	3.44	.98
500	76	.72	148	4.86	4.86	1.00
510	93	.89	145	6.14	5.95	1.03
520	97	.92	139	6.62	6.32	1.05
530	86	.82	127	6.45	5.95	1.08
540	70	.67	117	5.73	5.09	1.12
550	52	.50	107	4.67	3.94	1.18
560	35	.33	95	3.5	3.11	1.12
580	14.2	.135	72	1.88	1.50	1.25
600	4.1	.039	46	8.47	6.87	1.23

Table 5. NBS Remeasured Results for One Low Light Level Lamp Standard (Aug. 1975)

HIGH CURRENT (I= 4.0805 Amps)			LOW CURRENT (I= 3.4804 Amps)		
Wavelength (nm)	Spectral Radiance .6 X .8 mm Target (milliwatts·cm^{-3}·sr^{-1})	Gradient-corrected Spectral Radiance .6 X 5.6 mm Target (milliwatts·cm^{-3}·sr^{-1})	Wavelength (nm)	Spectral Radiance .6 X .8 mm Target (milliwatts·cm^{-3}·sr^{-1})	Gradient-corrected Spectral Radiance .6 X 5.6 mm Target (milliwatts·cm^{-3}·sr^{-1})
410	1.86252	1.77483	520	12.9256	12.3877
420	3.22955	3.08458	530	18.9252	18.1635
430	5.44627	5.21345	540	27.273	26.2117
440	8.94999	8.58593	550	38.7169	37.2606
450	14.358	13.8029	560	54.1917	52.2221
460	22.5222	21.6952	570	74.8417	72.2141
470	34.5965	33.3914	580	102.059	98.5995
480	52.1109	50.3907	590	137.519	133.018
490	77.0674	74.659	600	183.199	177.413
500	112.026	108.715	610	241.427	234.071
510	160.237	155.763	620	314.925	305.671
520	225.744	219.796	630	406.817	395.289
530	313.515	305.727	640	520.68	506.457
540	429.614	419.563	650	660.578	643.185
550	581.252	568.457	660	831.028	809.942
560	777.079	761	670	1037.12	1011.76
570	1027.16	1007.19	680	1284.51	1254.26
			690	1579.36	1543.53

Table 6. Luminance of Four RLS's - USAMCC vs NBS Data; Results as of 17 Nov 75

	High Green	Med. Green	Ratio (High/Med.)	High Yellow	Med. Yellow	Ratio (High/Med.)
AMCC	289	61.8	4.7	350	66	5.3
NBS	277	54.7	5.1	337	59.7	5.6
Ratio $(\frac{AMCC}{NBS})$	1.04	1.13		1.04	1.11	

(16)

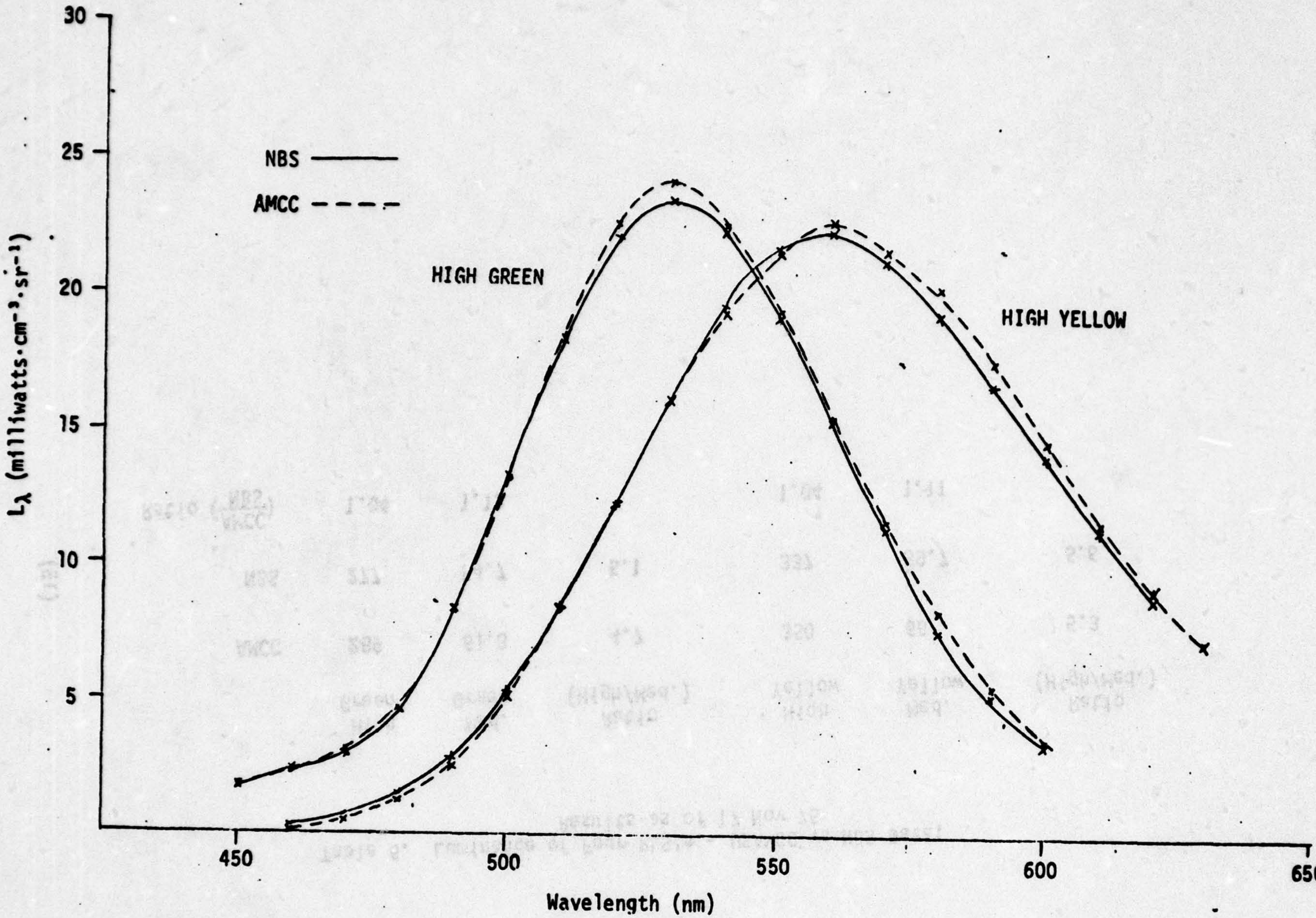


Fig. 2. Spectral Radiance vs Wavelength, High Green & High Yellow RLS's

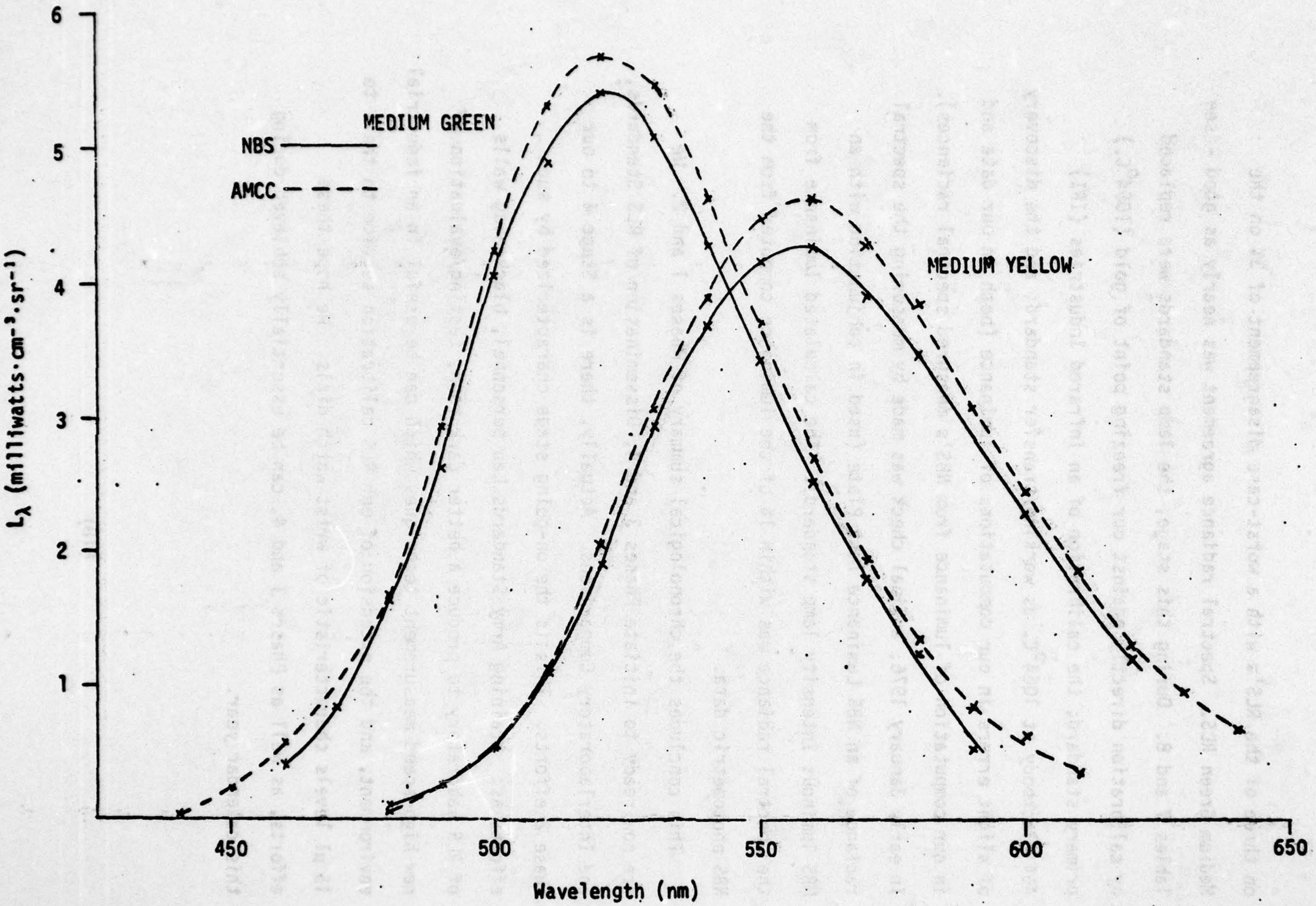


Fig. 3. Spectral Radiance vs Wavelength, Med. Green & Yellow RLS's

on three of the RLS's with a worst-case disagreement of 3% on the Medium Green RLS. Spectral radiance agreement was nearly as good - see Tables 7 and 8. During this stage, the lamp standards were replaced by calibration directly against our freezing point of gold (1064°C.) primary standard; the calibration of an Infrared Industries (IRI) 464 Blackbody at 1064°C. as working/transfer standard; and the discovery of slight errors in our computations of luminance (both in our data and in our computation of luminance from NBS's measured spectral radiances). In early January 1976, a final check was made by measuring the spectral radiance of an NBS Luminance Test Plate (used in conjunction with an NBS luminous intensity lamp standard). The calculated luminance from the spectral radiance was within 1% of the luminance computed from the NBS photometric data.

This concludes the chronological summary of Phases 1 and 2. We are now ready to initiate Phases 3 and 4, Dissemination of RLS Standards, and Interlaboratory Comparisons. Actually, there is a Stage 4 to our Phase 2 efforts. This is the on-going stage characterized by such efforts as: training Army Standards Lab personnel, blackening walls of RLS Laboratory to produce a better dark room, testing/evaluation of new high-speed measurement techniques which can be useful in an industrial environment, and the extension of our RLS calibration service to the 1 to 15 μl levels characteristic of wrist watch dials. We hope these efforts, as well as Phases 3 and 4, can be essentially achieved during this calendar year.

Table 7. Einal (Stage 3) Results, USAMCC bs NBS Data - High Yellow and High Green RLS's (December 1975)

Wavelength (nm)	HIGH YELLOW L_λ (NBS) ($mw \cdot cm^{-3} \cdot sr^{-1}$)	HIGH YELLOW L_λ(USAMCC)/L_λ(NBS) (-)	HIGH GREEN L_λ (NBS) ($mw \cdot cm^{-3} \cdot sr^{-1}$)	HIGH GREEN L_λ(USAMCC)/L_λ(NBS) (-)
450	-	-	1.85	1.059
460	.31	.935	2.40	.967
470	.80	.800	3.00	1.01
480	1.49	.933	4.82	.992
490	2.90	.969	8.40	.993
500	5.26	.971	13.30	.989
510	8.40	1.006	18.50	1.013
520	12.30	.985	22.10	1.012
530	16.10	.999	23.50	1.011
540	19.50	.987	22.30	1.007
550	21.60	.984	19.20	.997
560	22.30	.985	15.30	.992
570	21.30	.978	11.30	1.004
580	19.40	1.005	7.77	1.003
590	16.90	1.045	5.30	1.070
600	14.10	.993	3.46	.965
610	11.40	.887	2.20	.923
620	9.00	.964	-	-
630	7.00	.979	-	-

	PHOTOPIC LUMINANCE			SCOTOPIC LUMINANCE		
	NBS	USAMCC	USAMCC/NBS	NBS	USAMCC	USAMCC/NBS
High Yellow	343 µL	339 µL	.998	447 µL	441 µL	.987
High Green	283 µL	284 µL	1.003	652 µL	655 µL	1.005

Table 8. Final (Stage 3) Results USAMCC vs NBS Data - Medium Yellow and Medium Green RLS's (December 1975)

Wavelength (nm)	MEDIUM YELLOW L_λ (NBS) ($mw \cdot cm^{-3} \cdot sr^{-1}$)	MEDIUM YELLOW $L_\lambda(USAMCC)/L_\lambda(NBS)$ (-)	MEDIUM GREEN L_λ (NBS) ($mw \cdot cm^{-3} \cdot sr^{-1}$)	MEDIUM GREEN $L_\lambda(USAMCC)/L_\lambda(NBS)$ (-)
460	-	-	.42	.905
470	-	-	.85	.882
480	.12	1.083	1.65	.970
490	.31	.806	2.65	1.072
500	.57	.965	4.08	.997
510	1.13	1.000	4.92	1.049
520	1.96	.995	5.21	.965
530	2.94	.993	5.01	1.034
540	3.97	1.022	4.29	1.040
550	4.19	1.014	3.42	1.038
560	4.29	1.009	2.56	1.016
570	3.96	1.008	1.80	1.000
580	3.49	1.017	1.23	1.041
590	2.90	1.034	.81	1.074
600	2.32	.961	.53	1.038
610	1.70	.918	.35	.943
620	1.21	.983	-	-
630	.80	1.183	-	-

	PHOTOPIC LUMINANCE NBS	PHOTOPIC LUMINANCE USAMCC	PHOTOPIC LUMINANCE USAMCC/NBS	SCOTOPIC LUMINANCE NBS	SCOTOPIC LUMINANCE USAMCC	SCOTOPIC LUMINANCE USAMCC/NBS
Medium Yellow	61.0 µL	61.4 µL	1.007	74.5 µL	74.6 µL	1.001
Medium Green	56.7 µL	58.6 µL	1.034	154 µL	160 µL	1.039

3. DESCRIPTION AND CALIBRATION OF THE LOW-LIGHT-LEVEL SPECTRAL RADIANCE COMPARATOR.

Descriptions and calibrations herein and in the remainder of this report will be in terms of our present, refined configuration. Figures 4a-c are photos of our calibration setup within the RLS Laboratory, and Figure 5 is a photo of the four NBS-calibrated RLS's. Figure 6 schematically depicts the setup. It consists of the Transfer Standard IRI 464 Blackbody, source positioning equipment, Brower 131 Synchronous Voltmeter System, Gamma Scientific Telespectroradiometer, and shrouds and baffles as required. The IRI 464 Blackbody is transfer calibrated directly against our freezing-point of gold primary radiance standard blackbody via the spectral comparator. Results of our most recent intercomparison are as follows: The internal (imbedded) thermocouple indication to produce the same spectral radiance as the primary standard, at 560 nanometers is 10.395 ±.005 millivolts as measured on a John Fluke 887 Differential Voltmeter. However, because there is a small AC signal riding on the thermocouple leads, the positive polarity must be connected to the voltmeter's input; and the negative lead must be connected to the voltmeter's ground. Also relatively small temperature gradients within the cavity require defocusing, (in a clockwise direction) the telespectroradiometer's optics to produce a maximum indication. The signal increase from sharp visual focus to the defocused maximum indication is about 2%. Several runs against the gold point standard indicate that the stated thermocouple voltage will produce the gold point spectral radiance to within ±1%.

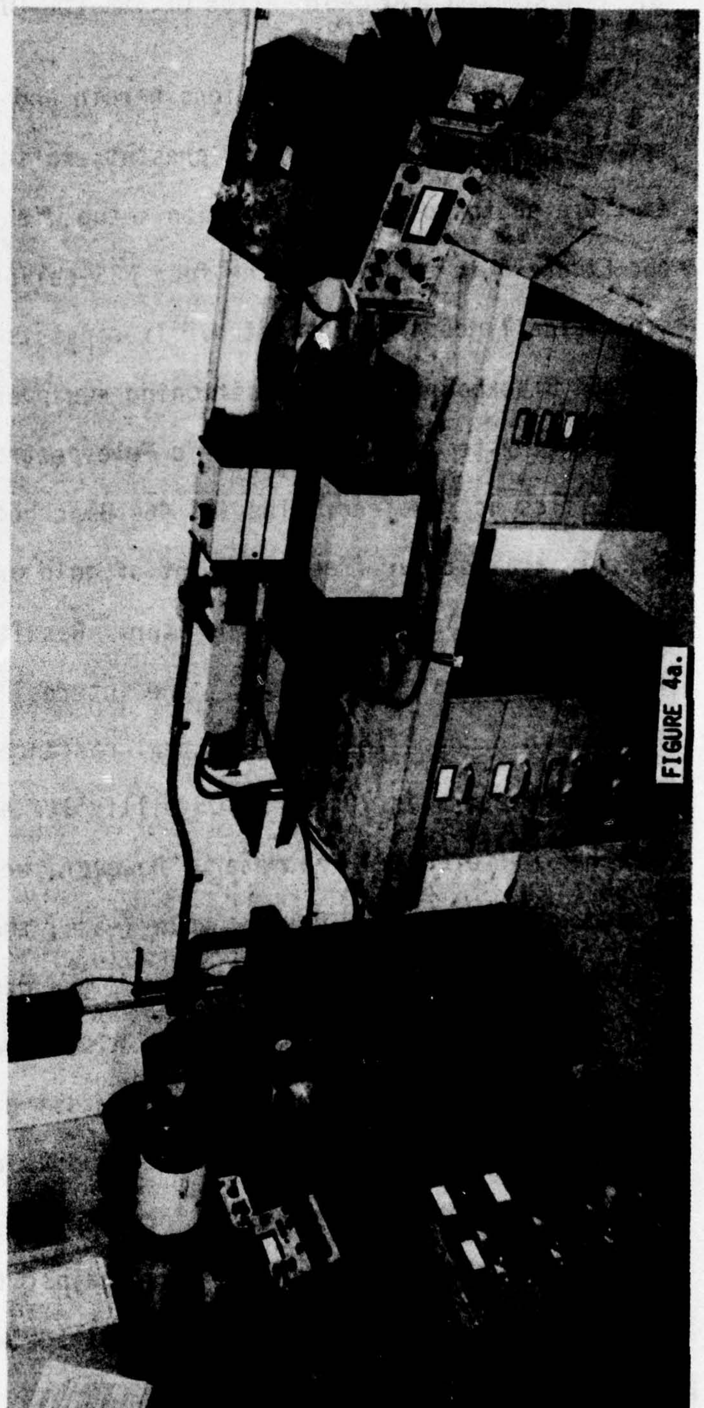


FIGURE 4a.

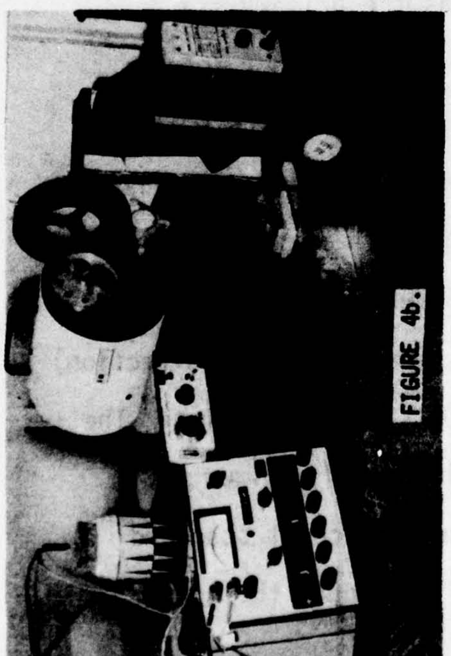


FIGURE 4b.

FIGURE 4c.

Figure 4a. Calibration Set-up in RLS Laboratory

Figure 4b. Closeup of Source and Working Standard (RLS Mounted in Center Foreground)

Figure 4c. Closeup of Telespectroradiometer and Brower Synchronous Voltmeter (Gamma Telephotometer in Foreground)

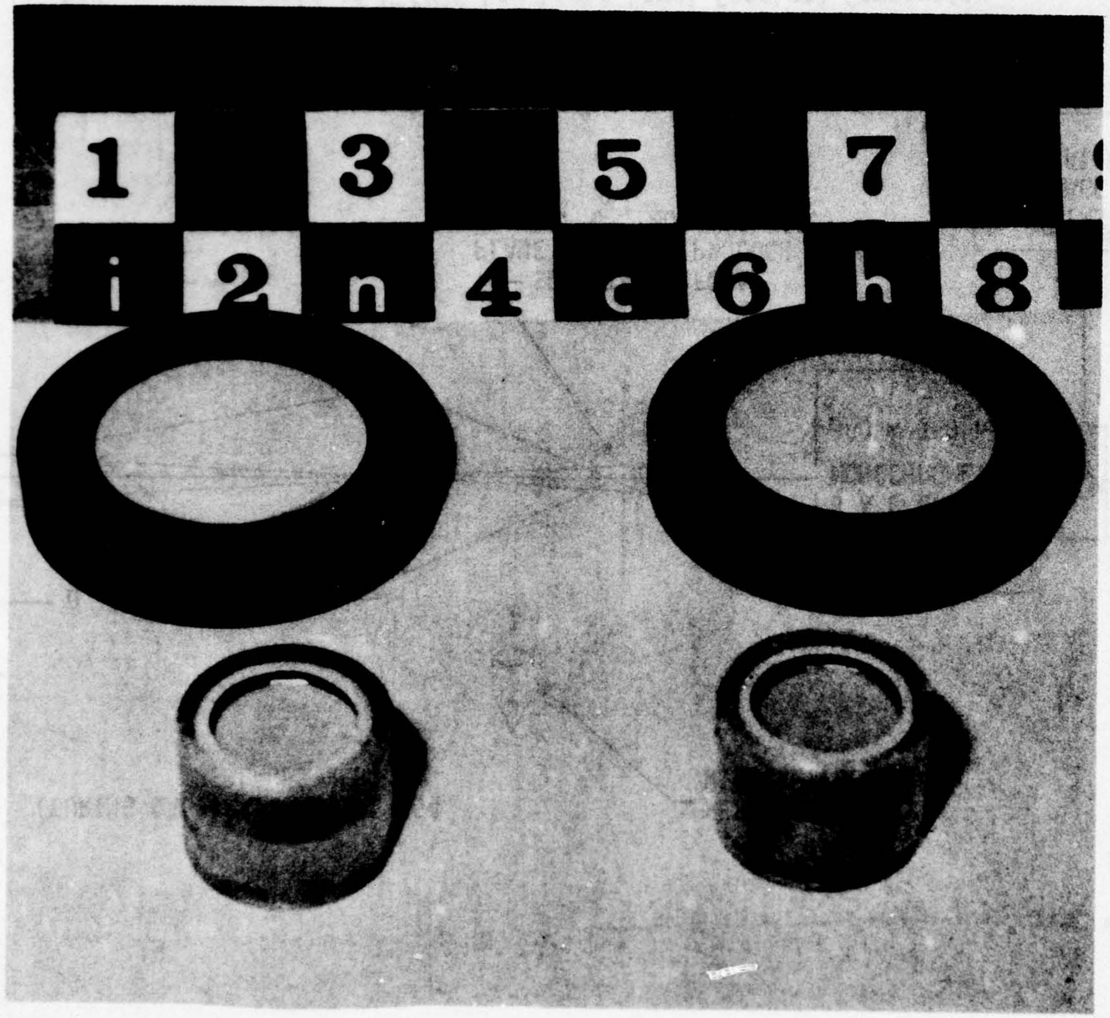


Figure 5. Photo of Four NBS-Calibrated RLS's

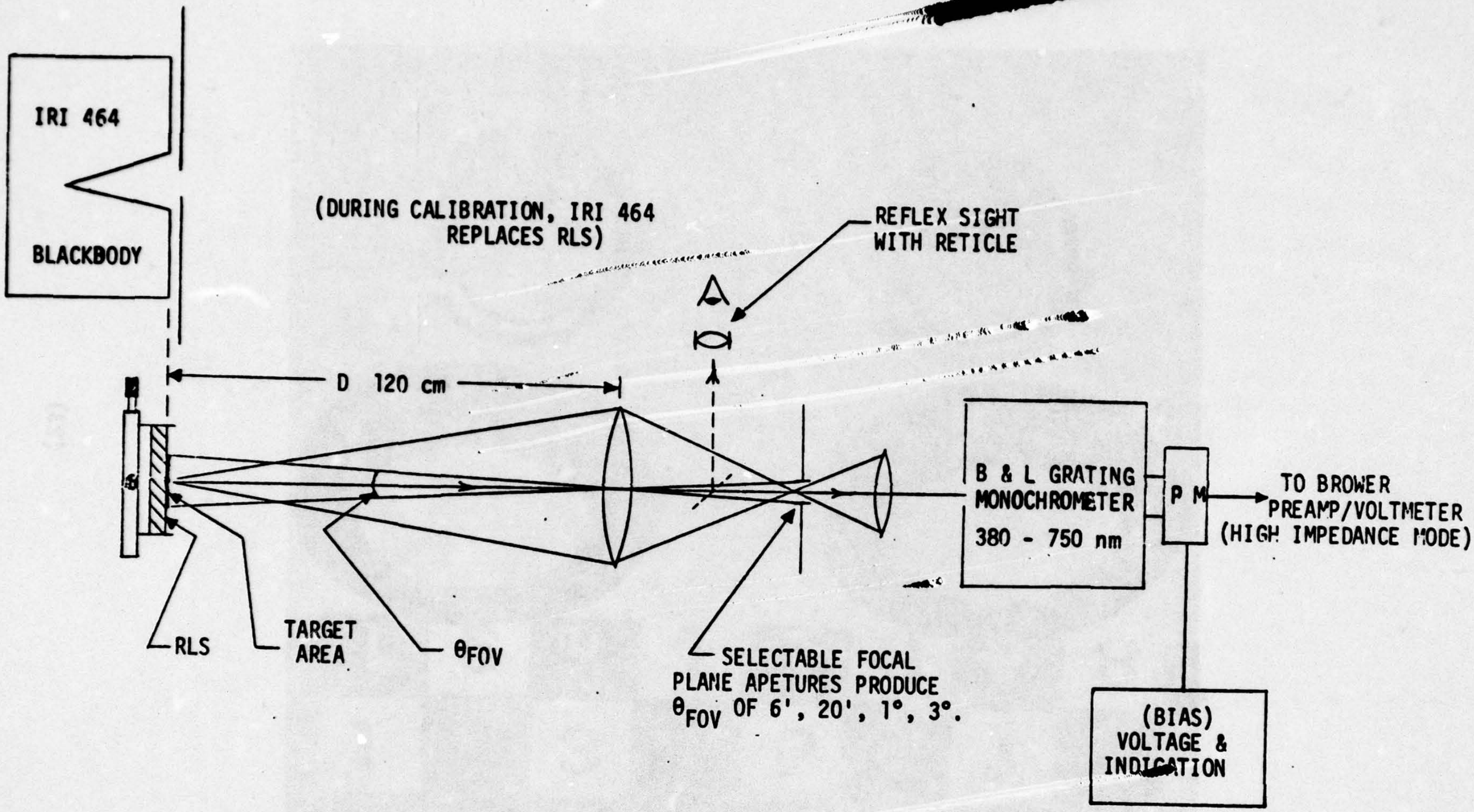


Fig. 5. Schematic of USAMCC Low Light Level Spectral Comparator

The Brower 131 Synchronous Voltmeter System consists of a mechanical chopper operated at 13 Hz which periodically interrupts the source radiation thus providing background discrimination. It also provides a sync signal to the remainder of the system: a (remote) preamp and synchronous voltmeter. Dynamic range of the Brower Voltmeter (HI-Z Mode) is 100 nanovolts to 5 volts; however, the telespectroradiometer's signals are confined to the range 1 mv to 1.5 volts, peak to peak. Note that the Brower does not have to read volts accurately; it only has to be linear and relatively stable. Over this restricted range of signals the voltmeter/telespectroradiometer has proven to be linear to ±1% or better.

The heart of our RLS spectral comparator is the Gamma Scientific Telespectroradiometer. It consists of an objective telescope focusable 3 feet to infinity; a Bausch and Lomb High Efficiency Grating Monocromator tunable from 350 to 800 nanometers; a 1P28 Photomultiplier; and a Display/Control Chassis which in our case only provides bias voltage and its indication. The signal voltage from the PM tube is disconnected from the display and routed to the Brower Voltmeter operated in the HI-Z (high input impedance) Mode. The optics are equipped with a reflex sight, and four selectable apertures (field stops) in the focal plane provide four FOV's, 6', 20', 1^{o}, and 3^{o}, for nominal optical gains of 1, 10, 100, and 1000 respectively. The reflex sight is equipped with a reticle of concentric rings which indicate the various FOV's.

Calibration of the telespectroradiometer consists of: wavelength calibration of the monochromator, calibration of the optical gain

associated with each FOV; and determination of the absolute spectral radiance responsivity, $R_L(\lambda)$, as a function of wavelength. In addition, the FOV shape and size are qualitatively assessed: the alignment - the visual line of sight as observed through the reflex sight - and the optical (radiometric) axis is checked; and the linearity and stability of the comparator are measured. The wavelength calibration is accomplished by using spectral lamps of mercury, sodium, and helium. Table 9 gives the results of the most recent determination of dial setting versus wavelength: No setting is more than 2 nanometers from the true wavelength.

The FOV shape and optical alignment is performed with an IRI 230 Collimator and an angular positioning table. The 20' and 1^{o} FOV's were checked, and the alignment checked in the 6' FOV. Maximum signal is very nearly coincident with the 6' FOV reticle indication; Figures 7a and 7b are plots of the 20' and 1^{o} FOV's. Since the FOV's are not flat, for high accuracy calibration it is imperative that the sources be uniformly radiating. In the case of viewing at 120 cm (our normal viewing distance) and the 1^{o} FOV (17.45 milliradians), a circular target area 21 mm in diameter is viewed, so RLS's must have at least this large an area which radiates uniformly.

The size of the FOV is most easily checked by viewing a ruler at measured distance. This measurement is not critical since the information is only used to estimate the size of uniform radiating area of RLS needed by our comparator. In practice, the prospective target area of

Table 9. Spectral Comparator Dial Setting vs Wavelength Using a Helium Lamp Source

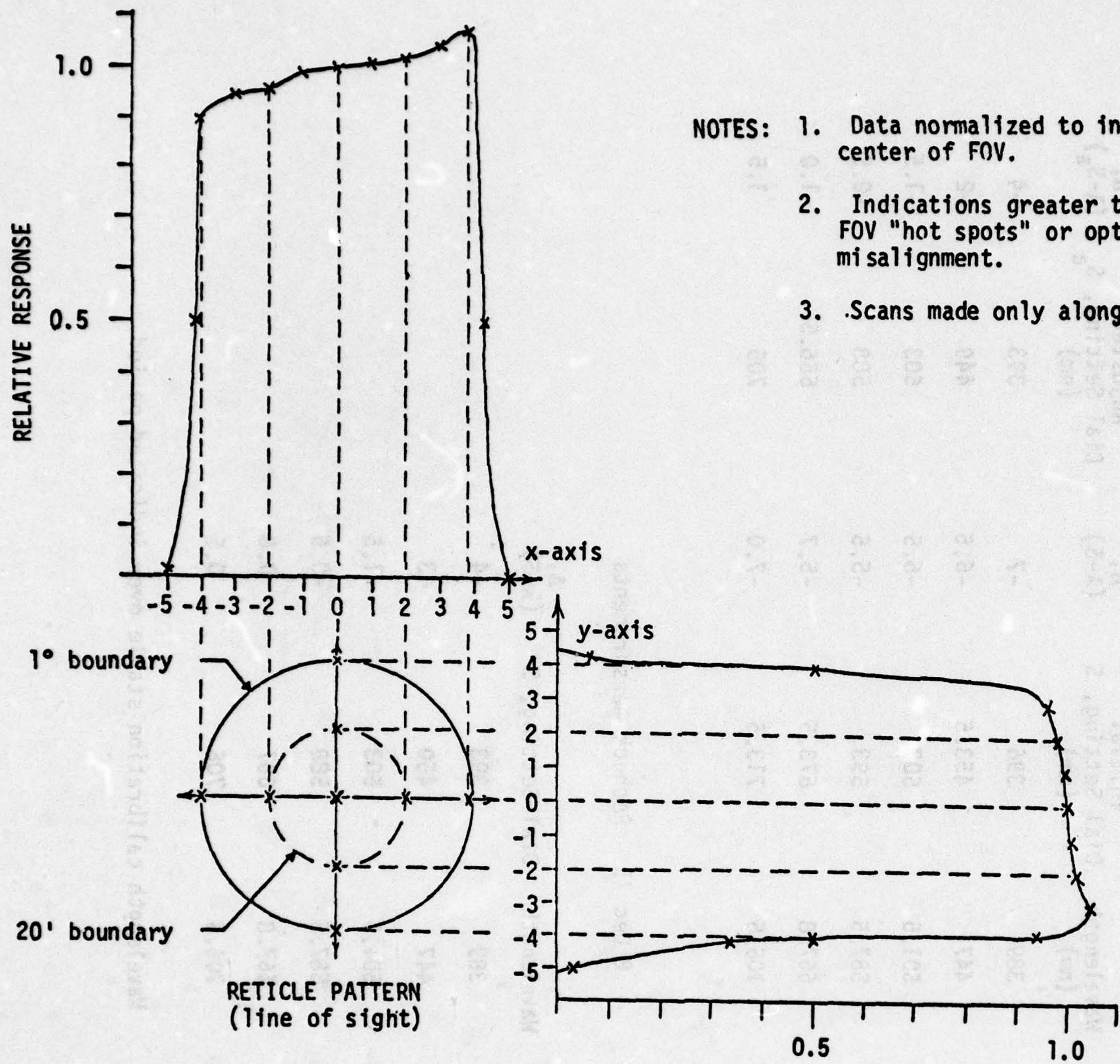
26 Aug 75 - Initial measurements indicating 6nm error

Wavelength (nm)	Initial Dial Setting, S (nm)	Δ, (λ-S)	Adjusted Dial Setting, S_a (nm)	Δ, $(\lambda-S_a)$
389	396	-7	393	-4
447	453.5	-6.5	449	-2
501.5	507	-6.5	503	-1.5
587.5	593	-5.5	588	-0.5
667.8	673.5	-5.7	666.5	-1.0
706.5	713.5	-7.0	705	1.5

8 Dec 75 - Recheck measurements

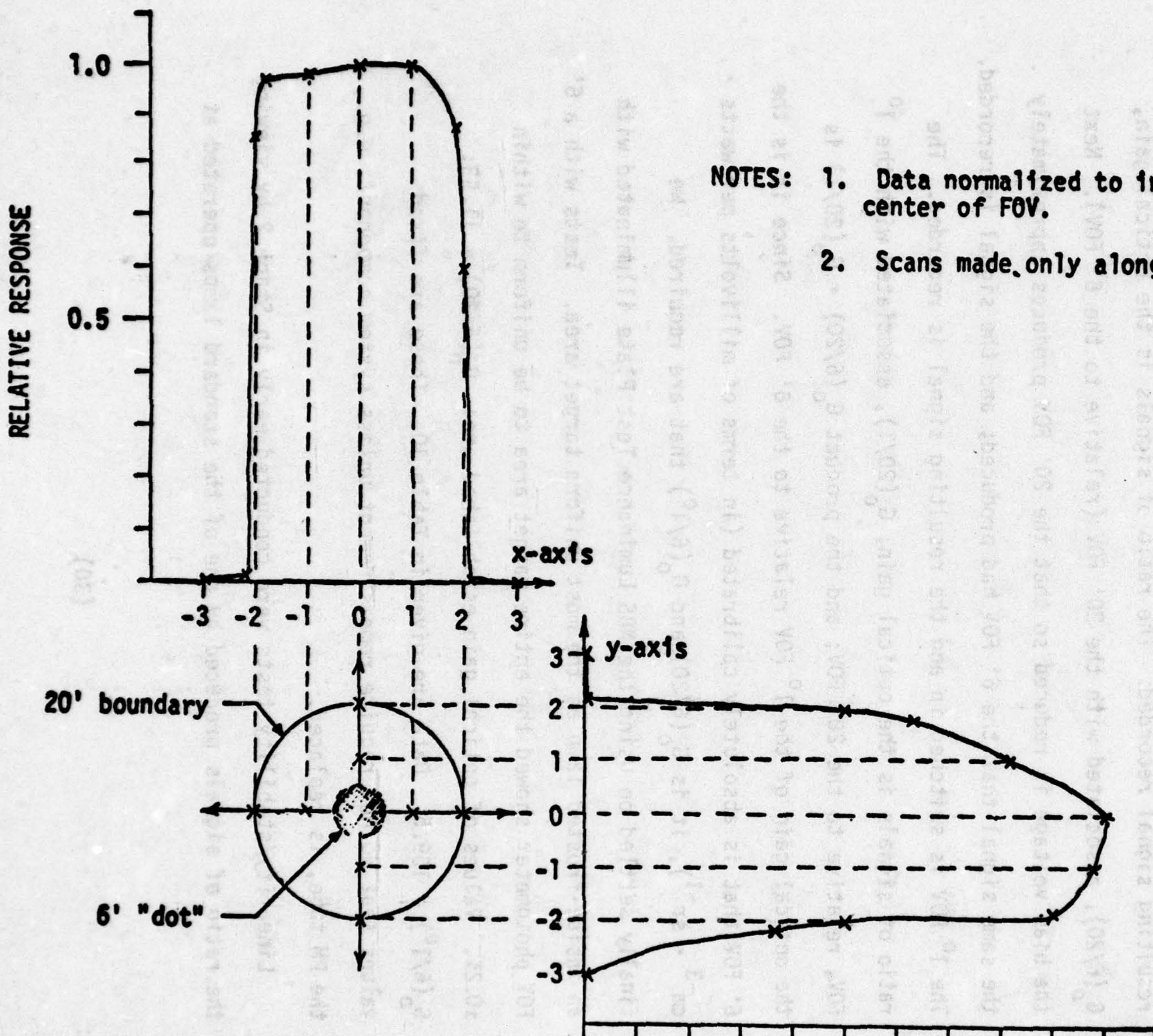
Wavelength	Dial Setting, S	Δ, (λ-S)
389	393	-4
447	450	-3
501.5	503	-1.5
587.5	588	-0.5
667.8	667	0.8
706.5	706	0.5

Wavelength calibration stable over indicated period.



NOTES:
1. Data normalized to indication at (visual) center of FOV.
2. Indications greater than unity indicate FOV "hot spots" or optical/visual axes misalignment.
3. Scans made only along x and y axes.

Fig. 6a. 1° FOV Plot



NOTES: 1. Data normalized to indication at (visual) center of FOV.

2. Scans made only along x and y axes.

the RLS is mapped with a 6' FOV photometer to assure reasonable, say, ±2%, uniformity.

The optical gain associated with each FOV is determined as follows: A uniformly illuminated target at least 25 mm in diameter is viewed by the 6' FOV and the signal recorded. The 20' FOV is switched in and the resulting signal recorded. The ratio of signals is the optical gain, $G_o(6/20)$, associated with the 20' FOV (relative to the 6' FOV). Next the bias voltage is reduced so that the 20' FOV produces approximately the same signal that the 6' FOV had produced; and the signal is recorded. The 1^o FOV is switched in and the resulting signal is recorded. The ratio of signals is the optical gain, $G_o(20/1)$, associated with the 1^o FOV, relative to the 20' FOV; and the product $G_o(6/20) \cdot G_o(20/1)$ is the optical gain of the 1^o FOV relative to the 6' FOV. Since it is the 6' FOV that is absolutely calibrated (in terms of millivolts per watts $\cdot$ $cm^{-3} \cdot sr^{-1}$), it is $G_o(6/20)$ and $G_o(6/1^o)$ that are required. We finally settled on using the NBS Luminance Test Plate illuminated with an inside-frosted lamp as the most uniform target area. Tests with a 6' FOV photometer showed the entire target area to be uniform to within ±0.2%. Values of optical gain established are: $G_o(6/20) = 11.53$; $G_o(6/1^o) = 109.5$. Data are given in Table 10. These are fixed values that do not require remeasurement unless system component, e.g., the PM tube, is replaced.

Linearity/stability tests were conducted early in Stage 2 by viewing the ratio of signals produced by one of the standard lamps operated at

Table 10. Test Data for Optical Gains Associated with 20' and 1° FOV's

FOV[1,2] (minutes)	Signal[3] (mv)	Ratio (FOV/6')	G_o (6/20)
6	70.6	11.56	11.53
20	816		
6	71.5	11.50	
20	822		
			G_o (6/20)
20	70.4	9.503	9.50
60	669		
20	70.7	9.505	
60	672		

1: Viewing NBS Luminance Test Plate

2 6' FOV Photometer indicates test plate uniform to about ± 0.2%

3: Signals are relative to 100mv full-scale indications on 10mv range of Brower

its two calibrated currents - refer to Figure 1. By comparing the signal levels and ratio of signals to the ratio of spectral radiances produced, we concluded that linearity was within our experimental repeatability: ±1% over the range 5 to 100 millivolts - see Table 11 for data. We then demonstrated linearity to 1.70 volts by a simple extension of the FOV test described above: The illumination of the test plate was adjusted to produce a signal of 25 millivolts when viewed with the 6' FOV. The 20' FOV was switched in and the voltage recorded. Since $G_o(6'/20') = 11.53$, we anticipated a signal of 288 millivolts. We observed 287 millivolts. Similarly, the illumination was adjusted to 150 millivolts in the 6' FOV, and the 20' FOV was again switched in. The expected voltage is 1.730 volts; the observed voltage was 1.700 volts, a difference of only 1.7%. Extension to these higher output voltages was required for observing the higher spectral radiances of the gold point blackbody standard.

During all of Stages 1 and 2 and the early part of Stage 3 refinement, the two lamps of low-light-level spectral radiance provided by NBS were the standards for calibrating our spectral comparator. Calibration consisted of determining the spectral radiance responsivity, $R_{L\lambda}(\lambda)$, as a function of wavelength, λ, in terms of (Brower) output per unit of spectral radiance input, i.e., in units of millivolts per watts $\cdot$ cm^{-3} $\cdot$ sr^{-1}*. The lamp standards were discarded in favor of the primary gold

*Watts $\cdot$ cm^{-3} $\cdot$ sr^{-1} equals 10^7 $\cdot$ watts $\cdot$ cm^{-2} $\cdot$ nm^{-1} $\cdot$ sr^{-1}; i.e., the spectral dependency, in units of nanometers has been incorporated with the area (cm^2) dependency. This is now standard terminology.

Table 11. Linearity of Spectral Comparator

Using Q-33 lamp standard; wavelength of 570 nm

Lamp Current	L_λ ($watt \cdot cm^{-3} \cdot sr^{-1}$)	Ratio (L_{Hi}/L_{Lo})	Comparator Data: Bias Voltage (DC volts)	Comparator Data: V^1 (mv)	Comparator Data: Ratio (V_{Hi}/V_{Lo})
High (4.0844 Amps)	1.057			100	
Low (3.4824 Amps)	.0783	.0741	785	7.4±0.1	.074 ± .001

Conclude: Linearity valid to within noise limitations, 10-100 mv range.

point blackbody standard in the middle of Stage 3 for several reasons. The most obvious is better accuracy, but the main reason was increased confidence in our calibration process. There existed the danger that the narrow lamp filaments were underfilling our 6' FOV (which would cause assignments of RLS spectral radiances to be systematically high). Second, NBS had provided gradient corrections vertically along the filament, but not horizontally. Since their corrections decreased the lamp spectral radiance anywhere from 3 - 5%, depending on wavelength, and since our target area did not coincide with theirs, we felt that an unnecessary uncertainty was being introduced. The final reason had to do with the only lamp which we had retained during/after NBS's recalibration efforts in mid-Stage 2. This lamp had strong positive gradients immediately adjacent to the nominal target area, making it virtually impossible not to introduce an additional ±3 - 4% uncertainty.

There are several factors which we considered in the switch to the gold point blackbody standard. The first is the need for the spectral comparator to be linear to the higher spectral radiances produced by the gold point blackbody (1337 Kelvin versus about 1180 Kelvin for the high current spectral radiance of the lamp standards.) Linearity to 1.70 volts has already been mentioned. The second point is determining the proper gain setting to produce responsivities consistent with the valid RLS measurement data (output voltages and NBS measurements) taken in Stage 2. We hit upon setting the bias voltage to produce a

spectral radiance responsivity of 110 mv/w · cm^{-3} · sr^{-1} at 560 nm, when the gold point blackbody was in a freeze. This set point was chosen for the following reasons: The "good" lamp standard* of spectral radiance produced a responsivity of 110 at 560 nanometers when the NBS gradient correction was used; and the "High Green" RLS, used as a standard also produces a responsivity of 110. Thus, we forced data agreement at 560 nanometers and observed the spectral responsivity at all other wavelengths (440-700 nm). Then these spectral radiance responsivities were used to assign the spectral radiances of all four NBS-measured RLS's. How do we know that the responsivities produced in this way apply to previously measured data? Is this not just a normalization trick that simply forces agreement that did not exist when the four RLS's were actually measured? The answer is: We don't know, with complete certainty, that these latest responsivities (which are highly accurate for present and future measurements) apply to the previously measured data. The bias voltages are certainly different (800 VDC versus the present 820-830 VDC). Nevertheless, we believe the present responsivities do apply. The key reason for our belief is that the standard lamp, at the time of the measurements, produced essentially the same responsivity at 560 nanometers, namely 109.7 millivolts/watts · cm^{-3} · sr^{-1}; and this was the basis of setting the gain of the spectral comparator when observing the gold point standard. This, and the sheer consistency of the data, we believe, are rather compelling arguments.

The final factor in considering use of the gold point blackbody as the

*"Good" in this context means the maximum spectral radiance occurs in the center of the filament coincident with the target area.

standard for our low-light-level spectral radiance comparator, was the need for a reliable transfer or working standard. The primary standard is, after all, a bulky, cumbersome apparatus which is not portable and not well-designed for daily use. Several runs against the gold point convinced us that the comparator was not stable on a day-to-day or even a run-to-run basis: bias voltages to produce an R_L of 110 varied from 800 to 830 VDC, with a 1 volt bias change producing about a 1% change in output. Therefore, considerable effort was expended to find some source which was precisely reproducible to transfer the gold point calibration. We tried the NBS lamp (at this time, we only had the one with a strong gradient above the target area), but discarded it because of the ±4% nonreproducibility. Note that this nonreproducibility is not in the lamp per se. It is the result of parallax in visual sighting which does not allow precise resetting of the lamp-comparator target area. Hot spots on a Gamma Scientific 220-9 Luminance Source produced similar ambiguities. But the IRI 464 Blackbody, while containing gradients, produced reproducible results independent of the parallax problem.

In January 1976, we measured the spectral radiance of an NBS Luminance Test Plate illuminated by an NBS lamp standard of luminous intensity. The spectral comparator was calibrated against the IRI 464 Blackbody immediately prior and subsequent to taking test data. The calculated luminance and NBS-assigned luminance agreed to within 1%,—see Table 12 for the data. Column 3 contains the accepted values of spectral radiance responsivity versus wavelength, when the gain is adjusted

Table 12. Measurement Data for NBS Standard Luminance Test Plate

Standards: NBS Candela Lamp #9706 (753 cd)
NBS Lum. Test Plate #LS622 (.428 FT.L/FT.C)

Source/Test Plate Distance: 104.5 cm

COMPARATOR DATA FOV=6'

Wavelength (nm)	Brower Voltage (mv)	$R_{L\lambda}$[1] $(mv/mw \cdot cm^{-2} \cdot sr^{-1})$
440	58	179.2
460	80	179.6
480	102	174.6
500	125	171.8
520	143	159.5
540	146	135.5
560	139	110.0
580	127	86.1
600	84.5	51.0
620	41.5	22.7
640	25.0	12.1
660	15.0	6.6
680	8.80	3.5
700	5.05	1.9

LUMINANCE

NBS	USAMCC	USAMCC/NBS
27.42 FT.L	27.16 FT.L	1.01

NBS & USAMCC Luminance values agree to within 1%.

[1] Gain of comparator set to produce $R_{L\lambda}$ = 110 with λ = 560nm when observing IRI 464 working standard.

to produce 110 millivolts/watts $\cdot$ cm^{-3} $\cdot$ sr^{-1} at 560 nanometers. This completed the checkout of our low-light-level spectral radiance comparator, including its transfer standard.

4. CONCLUSIONS AND RECOMMENDATIONS.

Our main conclusion is that we have developed a highly accurate calibration service for low-light-level sources, primarily RLS's. Reviewing the uncertainties, the primary standard gold point blackbody introduces negligible error, but the transfer to the working standard, the IRI 464 introduces uncertainty of perhaps ±1%. Use of the working standard/readability of the Brower Voltmeter introduces another ±1%, i.e., a total comparator calibration/use error of ±2%. Remaining errors are essentially associated with RLS nonuniformities. These are usually in the neighborhood of ±3% when a target area 20 mm in diameter is scanned by a 6' FOV photometer (spot size of 2 mm). Since measurement of four NBS-calibrated RLS's produces agreement to ±1% on three and a +3% worst-case disagreement on the fourth, it seems reasonable to assign an overall uncertainty of $3.6\% = \sqrt{3^2 + 2^2}$ to our spectral comparator system, for luminance levels in the range 25 - 1500 microlamberts. This exceeds our expectations by about a factor of two.

This calibration service will be offered to Army and DOD customers upon receipt of our NRC license. In the interim, this service is immediately available if users wish to handcarry the RLS to USAMCC. Point of contact is Mr. Delbert Loney, AUTOVON 746-5042, or Mr. Charles Harper, AUTOVON 746-5528, to schedule calibration/visit details.

Recommendations relate mainly to follow-up and on-going efforts. Follow-up details include final setup of the RLS laboratory, including bench layout and darkening of walls with black cloth; rework of our data reduction/analysis computer program to include calibration certificate

preparation; and training of Army Standards Lab personnel. Recommended on-going efforts are: dissemination of calibrated RLS's, conducting interlaboratory comparisons, and extension of accurate RLS calibration to the 1 - 25 μl range. This latter effort will take a considerable amount of time and additional, more sensitive, equipment, since both we and NBS encounter noise problems at levels below about 25 μl. We have in mind evaluating the Princeton Applied Research Optical Multichannel Analyzer (OMA) with a cooled optical head for this range extension. This device also promises faster data collection and reduction as it appears that it can be computer-interfaced directly. Alternatively, it may be possible to achieve reasonable accuracy (±5%) by careful calibration of a broadband photometer, combined with radiometric corrections (see Appendix B). This approach has considerable promise and will also be investigated. It is hoped that this extension could attain basic operational capability in about one calendar year, with refinements probably continuing for another six months.

APPENDIX A

LUMINANCE CALCULATIONS

This Appendix provides the information needed to calculate luminance, either photopic or scotopic, based on spectral radiance data, and accepted values of photopic and scotopic luminosity. Our "accepted" values were the same as NBS's, namely Wyszecki and Stiles, Color Science, (John Wiley & Sons, Inc., New York, N.Y., 1967), pp 378, 384. Table A-1 gives the values listed in that book.

The equation we use to compute photometric luminance is:

$$L_p = 213.6 \sum_{n=1}^{N} L_\lambda(\lambda) \cdot V_\lambda(\lambda) \qquad [\mu L] \qquad (1a)$$

and the one we use for scotopic luminance is:

$$L_s = 548.2 \sum_{n=1}^{N} L_\lambda(\lambda) \cdot V'_\lambda(\lambda) \qquad [\mu L] \qquad (1b)$$

where L_λ = spectral radiance, expressed in $w \cdot cm^{-2} \cdot nm^{-1} \cdot sr^{-1}$

V_λ, V'_λ = the relative response curves for photopic and scotopic vision, respectively; and

N = number of points observed in the wavelength interval 400-700 nm, usually 15-20.

These are derived as follows. In general:

$$B_p = K_m \int_{400}^{700} L_\lambda \cdot V_\lambda d\lambda \qquad [lm \cdot cm^{-2} \cdot sr^{-1}] \text{ or } [stilbs] \qquad (2a)$$

TABLE A1. TABLE OF LUMINANCE EFFICIENCY VALUES

Wavelength (nm)	Photopic V_λ	Scotopic V_λ
380	0000	0006
390	0001	0022
400	0004	0093
410	0012	0348
420	0040	0966
430	0116	1998
440	0230	3281
450	0380	4550
460	0600	6670
470	0910	0760
480	1390	7930
490	2080	9040
500	3230	9820
510	5030	9970
520	7100	9350
530	8620	8110
540	9540	6500
550	9950	4810
560	9950	3288
570	9520	2076
580	8700	1212
590	7570	0655
600	6310	0332
610	5030	0159
620	3810	0074
630	2650	0033
640	1750	0015
650	1070	0007
660	0610	0003
670	0320	0001
680	0170	0001
690	0082	0000
700	0041	0000

$$B_s = K'_m \int_{400}^{700} L_\lambda \cdot V'_\lambda d\lambda \qquad (2b)$$

where K_m = 680 l/w ; K'_m = 1746 l/w are conversion factor, respectively, for photopic and scotopic vision. The relationship between brightness and luminance is:

$$L = \pi B \qquad [\text{Lamberts}] \qquad (3)$$

where B is in terms of stilbs. Now the spectral radiances are reported in terms of $w \cdot cm^{-3} \cdot sr^{-1}$; and the conversion factor to $w \cdot cm^{-3} \cdot sr^{-1} \cdot nm^{-1}$ is just 10^{+7} nm/cm. Thus, we have:

$$L_p = 680 \cdot \pi \cdot 10^{-7} \int L_\lambda(\lambda) \cdot V_\lambda(\lambda) d\lambda \qquad [L] \qquad (4)$$

or, expressed in microlamberts:

$$L_p = 68 \cdot \pi \int_{400}^{700} L_\lambda(\lambda) \cdot V_\lambda(\lambda) d\lambda \qquad [\mu L] \qquad (5a)$$

and

$$L_s = 174.6 \cdot \pi \int_{400}^{700} L_\lambda(\lambda) \cdot V'_\lambda(\lambda) d\lambda \qquad [\mu L] \qquad (5b)$$

Generally we integrate using Trapezoidal Rule, with a wavelength increment of $\Delta\lambda$ = 10 nm. Thus, we normally have:

$$L_p = 2136 \sum_{n=1}^{N} L_\lambda \cdot V_\lambda \qquad [\mu L] \qquad (6a)$$

$$L_s = 5482 \sum_{n=1}^{N} L_\lambda \cdot V'_\lambda \qquad [\mu L] \qquad (6b)$$

which are essentially equations 1a, 1b.

The conversion factor, from microlamberts to footlamberts is:

$$1 \text{ ft. L} = 1076.4 \ \mu\text{L} \qquad (7)$$

APPENDIX B

RADIOMETRIC CORRECTIONS TO PHOTOMETRIC INDICATIONS

During late Stage 2, in an effort to resolve our discrepancies with NBS and improve our measurement accurancy, we attempted to correct the indications of a calibrated photometer, using the spectroradiometric data. In general, we have:

$$(\mathrm{IND}) = R_L \int_0^\infty L_\lambda(\lambda)\cdot r_p(\lambda)\cdot d\lambda \qquad [\mathrm{volts}] \qquad (1)$$

where IND = the photometer's output indication, usually expressed in volts;

R_L = peak-normalized ("effective") radiance responsivity $V/w \cdot cm^{-2} \cdot sr^{-1}$;

$r(\lambda)$ = relative spectral responsivity of the radiometer (photometer); and

$L_\lambda(\lambda)$ = spectral radiance of the source $w \cdot cm^{-2} \cdot sr^{-1} \cdot nm^{-1}$

where the integration is over all wavelength where the product function $L_\lambda \cdot r(\lambda)$ is non-zero. The photometer manufacturer tries to design his photometer so that the relative spectral responsivity, $r_p(\lambda)$, matches the C.I.E. photopic response curve, $V_\lambda(\lambda)$. Note that, if $r(\lambda) = V_\lambda(\lambda)$, we have:

$$(\mathrm{IND}) = R_L \int_{400}^{700} L_\lambda(\lambda)\cdot V_\lambda(\lambda)\cdot d\lambda \qquad [\mathrm{volts}] \qquad (2)$$

$$= R_L\,(L_v/\pi K_m)$$

where L_V = the true luminance in lamberts; but the quantity in parenthesis, i.e., the integral in equation 2 is still an "effective" radiometric radiance. It is only when R_L is adjusted, in a calibration process, equal to πK_m, that this "perfect" photometer will provide direct indications of luminance*.

Returning to equation 1, suppose we observe a known or calibration source of luminance, such as the NBS Luminance Test Plate, or the freezing point of gold blackbody. Then:

$$(IND)_c = R_L \int L_{\lambda,c}(\lambda) \cdot r_p(\lambda) \cdot d\lambda \qquad (3)$$

where the subscript, c, indicates that the photometer is observing the calibration source whose spectral radiance is $L_{\lambda,c}(\lambda)$. Normally the photometer gain is adjusted so that, for the calibration source at least, the photometer is direct-indicating:

$$(IND)_c = R_L \int_0^{\infty} L_{\lambda,c}(\lambda) \cdot r_p(\lambda) \cdot d\lambda$$

$$\doteq \pi K_m \int_{400}^{700} L_{\lambda,c}(\lambda) \cdot V_\lambda(\lambda) \cdot d\lambda \qquad [L] \qquad (4)$$

where the symbol, $\doteq$, indicates adjustment to produce direct-indications for at least standard spectral distributions. Usually the standard distribution is taken to be the 2856K spectral distribution of the "white light" NBS candela standards. The degree to which this calibration

*Of course, the calibration process may only determine the relationship between R_L and πK_m. In that case, luminance may be measured by reference to calibration data, but the photometer will not be direct-indicating.

is valid for accurate measurements of non-white sources, e.g., the RLS spectral distributions, depends on the fit of the relative spectral responsivity, $r_p(\lambda)$ to the photopic eye response curve V_λ. But in principle, if $r_p(\lambda)$ is known, the spectral radiance, or at least the spectral shape -- the normalized spectral radiance -- is known, correction factors can be calculated to convert the photometer's indications to true luminance of the unknown source. We have:

$$(IND)_u = R_L \int_0^\infty L_{\lambda,u}(\lambda)\cdot r_p(\lambda)\cdot d\lambda \quad \text{"Lamberts"} \qquad (6)$$

where, from equation 4,

$$R_L = \frac{\pi K_m \int_{400}^{700} L_{\lambda,c}(\lambda)\cdot V_\lambda(\lambda)\cdot d\lambda}{\int_0^\infty L_{\lambda,c}(\lambda)\cdot r_p(\lambda)\cdot d\lambda} \qquad (7)$$

Rearranging equation 6, we have:

$$\int_0^\infty L_{\lambda,u}(\lambda)\cdot r_p(\lambda)\cdot d\lambda = (IND)_u/R_L \qquad (8)$$

Now, if we multiply both sides of equation 8 by the quantity:

$$\pi K_m \int_{400}^{700} L_{\lambda,u}(\lambda)\cdot V_\lambda(\lambda)\cdot d\lambda \Big/ \int_0^\infty L_{\lambda,u}(\lambda)\cdot r_p(\lambda)\cdot d\lambda \qquad (9)$$

We obtain:

$$L_v \equiv \pi K_m \int_{400}^{700} L_{\lambda,u}(\lambda)\cdot V_\lambda(\lambda)\cdot d = \frac{(IND)_u}{R_L}\left[\frac{\pi K_m \int_{400}^{700} L_{\lambda,u}(\lambda)\cdot V_\lambda\cdot d\lambda}{\int_0^\infty L_{\lambda,u}(\lambda)\cdot r_p(\lambda)\cdot d\lambda}\right] \qquad (10)$$

Note that $L_{\lambda,u}$, πK_m, and $L_{\lambda,c}$ appear in both numerator and denominator, allowing removal (cancellation) of the quantitative numbers. We need only the relative values of the spectral radiances, $l_{\lambda,c}(\lambda)$, etc., where:

$$l_\lambda \equiv L_\lambda(\lambda)/L_\lambda(\lambda_p) \qquad \text{[dimensionless]} \qquad (11)$$

and where $L_\lambda(\lambda_p)$ = the maximum spectral radiance of the source which occurs at a wavelength, λ_p. Finally, substituting (11) into (10) we obtain the equation for converting photometric indications to luminance values:

$$L_v = (IND)_u \frac{\int_0^\infty l_{\lambda,c}(\lambda)\cdot r_p(\lambda)\cdot d\lambda}{\int_{400}^{700} l_{\lambda,c}(\lambda)\cdot V_\lambda(\lambda)\cdot d} \; \frac{\int_{400}^{700} l_{\lambda,u}(\lambda)\cdot V_\lambda(\lambda)\cdot d\lambda}{\int_0^\infty l_{\lambda,u}(\lambda)\cdot r_p(\lambda)\cdot d\lambda} \qquad [L] \qquad (12)$$

We attempted to use this approach to improve our accuracy, since the photometer offered significantly increased signal-to-noise ratios (SNR's). The most difficult part was accurately measuring the photometer's relative spectral response, $r_p(\lambda)$. Figure B-1 shows two measurements, plotted with the C.I.E. photopic eye response for comparison. Note that either curve fits the V_λ curve quite well; but the one marked "new" $r_p(\lambda)$ is our best estimate as of now. Substituting this value; the spectral radiances of the NBS Luminance Test Plate for $L_{\lambda c}(\lambda)$*; and the best USAMCC measurements for the RLS's spectral radiances (i.e.,

*The photometer, a Gamma Scientific 2009, was carefully calibrated to be direct-reading against this standard.

the Stage 3 final results), we obtain the following correction factors:

Table B-1. Photometric Correction Factors

1. Calibration Source Correction Factor: .897
2. Correction Factors for RLS:
   a. Hi Green - 1.099
   b. Hi Yellow - 1.088
   c. Medium Green - 1.103
   d. Medium Yellow - 1.082

Using these correction factors, the RLS's were observed. We obtained the results shown below:

Table B-2. RLS Photometric Results

Source	NBS Luminance (μl)	Photometer Indication	Corrected Indication (μl)	Ratio (Corrected/NBS)
Hi Green	283	302	298	1.053
Medium Green	56.7	60.6	60	1.058
Ratio $\frac{\text{Hi G}}{\text{Med G}}$	4.99	4.98	4.97	--
Hi Yellow	343	360	351	1.023
Medium Yellow	61	62.1	60.3	1.012
Ratio $\frac{\text{Hi Y}}{\text{Med Y}}$	5.62	5.80	5.82	--

The corrections amount to only about 2%, but they are in the right direction. We don't know at this time, why the corrections don't work better. Contributing errors are the repeatability and linearity of the photometer, RLS non-uniformity, and especially the criticality of the $r_p(\lambda)$ measurement. If we use the other $r_p(\lambda)$ curve, the correction factors fit the data considerably better. We conclude that this technique is promising, but more measurements with NBS will be required to obtain accuracies approaching the spectral comparator. Since it gives agreement to 5%, and since RLS inaccuracy is about ±5%, we suspect that using calibrated RLS's as standards in a new interlaboratory comparison should produce agreement to ±10%.